Diboson Production and Drell-Yan Forward-Backward Asymmetry Measurements using the DØ Detector at Fermilab

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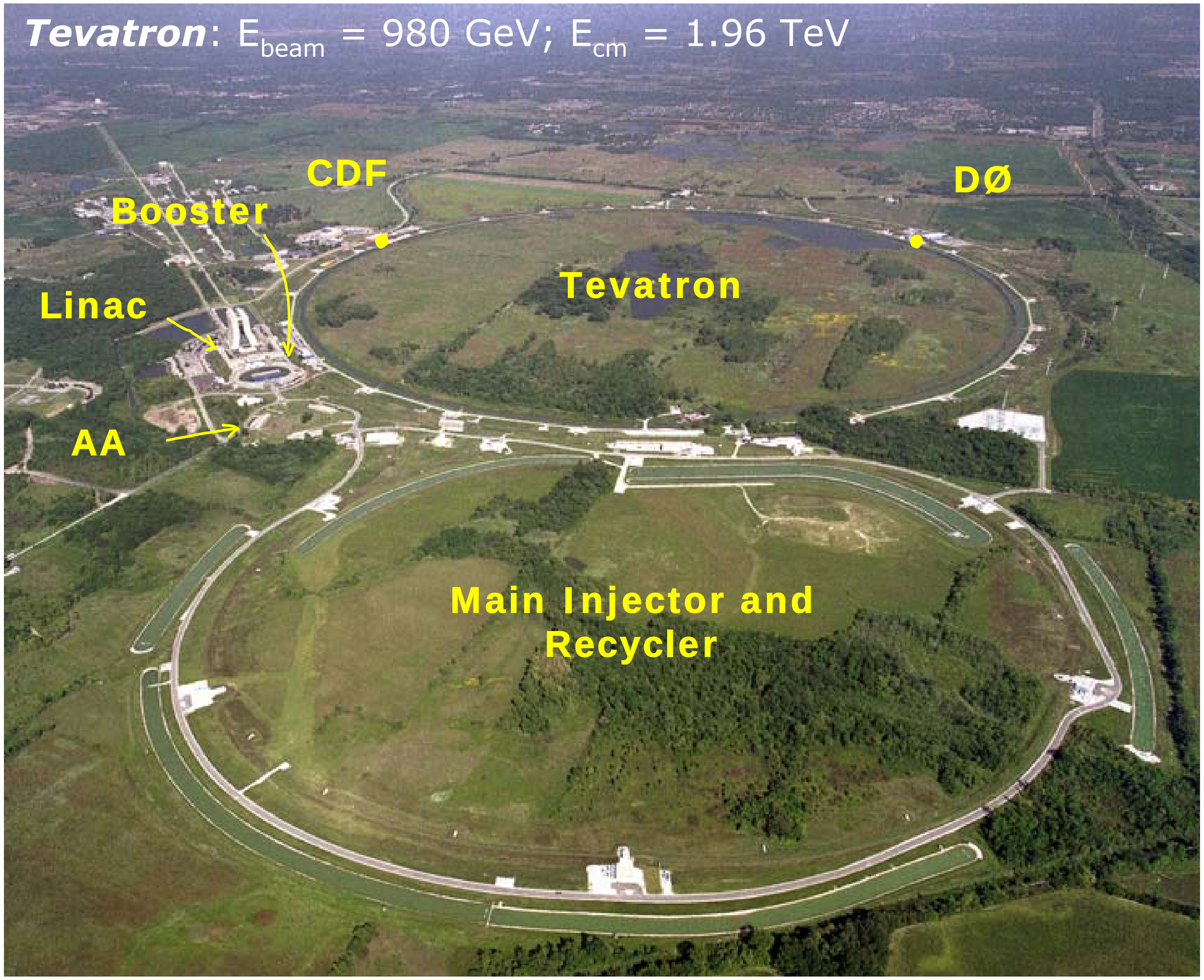
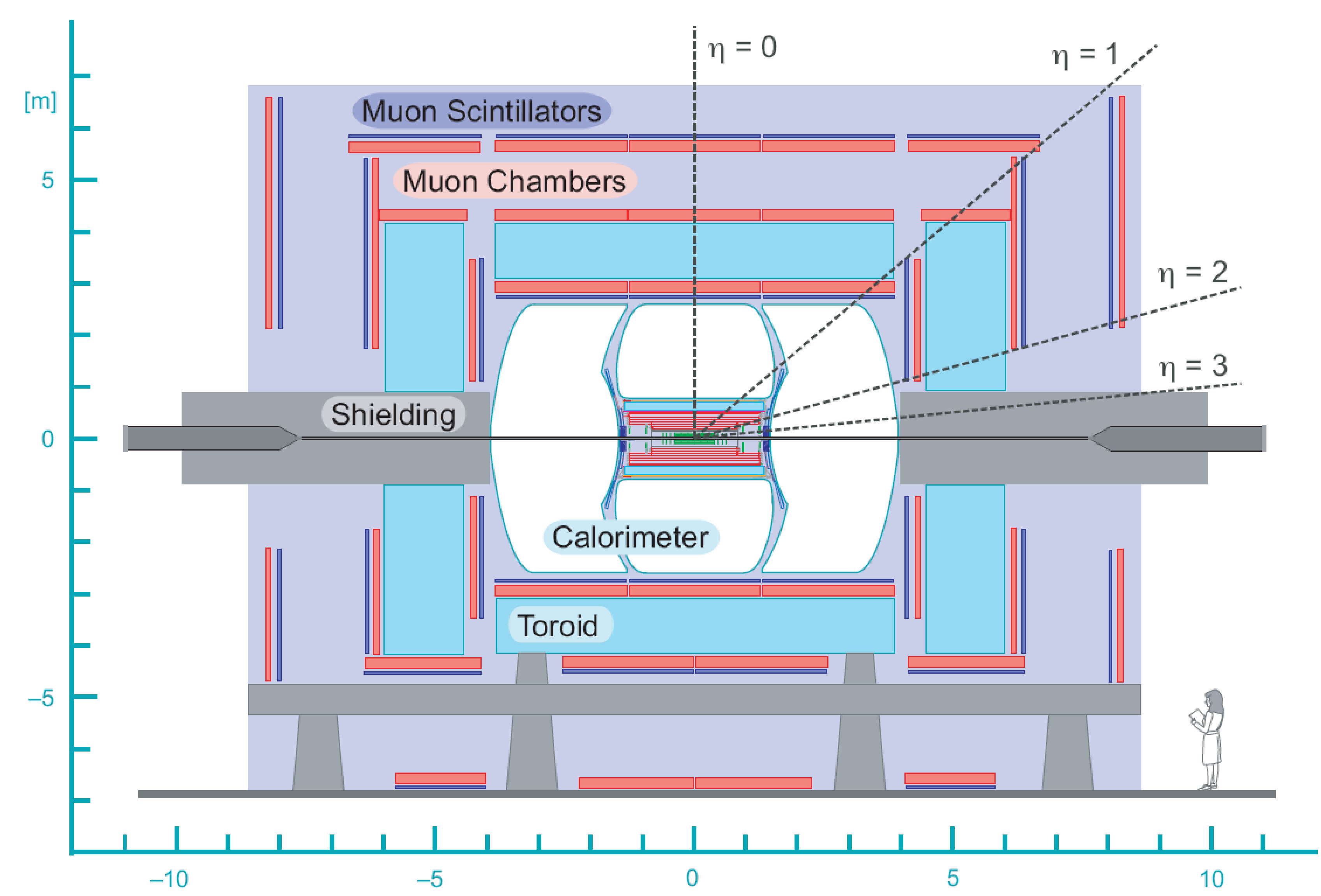
The Tevatron



- DØ data recorded to date ~ 0.7 fb^{-1}
- Results shown in this talk are based on ~ 150–320 pb^{-1}
- Expect ~ 1 fb^{-1} by Fall 2005
- ~ 4-8 fb^{-1} by 2009

The DØ Detector



The WWγ and WWZ Vertices

- Standard model $U(1)_Y \times SU(2)_L$ predicts existence of gauge boson self-interactions
- Direct measurement:
  - Demonstrate SM predictions are correct, or not…
  - Use as probe of new physics
- ***Effective Lagrangian*** parametrization of new physics in terms of coupling parameters
  - SM tree-level values:

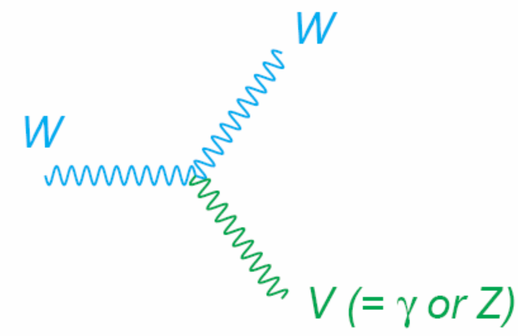
$$g_1^V = 1 \quad \left(\Delta g_1^V \equiv g_1^V - 1 = 0\right)$$
$$\kappa_V = 1 \quad \left(\Delta \kappa_V \equiv \kappa_V - 1 = 0\right)$$
$$\lambda_V = 0$$

- Unitarity violation avoided by use of ***form factor***

$$a(\hat{s}) = \frac{a_0}{\left(1 + \hat{s}/\Lambda_{FF}^2\right)^2}$$

$\hat{s}$ = subprocess CM energy

Λ_{FF} = form factor scale related to scale of new physics



$$L_{WWV}/g_{WWV} = i g_1^V \left(W_{\mu\nu}^\dagger W^\mu V^\nu - W_\mu^\dagger V_\nu W^{\mu\nu}\right)$$
$$+ i\kappa_V W_\mu^\dagger W_\nu V^{\mu\nu}$$
$$+ i\frac{\lambda_V}{m_W^2} W_{\lambda\nu}^\dagger W_\nu^\mu V^{\nu\lambda}$$
$$+ \text{CP-violating terms}$$

- WWγ couplings related to magnetic dipole and electric quadrupole ***moments of the W***

$$\mu_W = \frac{e}{2m_W}\left(1 + \kappa_\gamma + \lambda_\gamma\right)$$

$$Q_W^e = -\frac{e}{m_W^2}\left(\kappa_\gamma - \lambda_\gamma\right)$$

Expectations for Couplings

- Expected values of WWγ couplings in SM and some models beyond the SM

Model	$\lvert\Delta\kappa_\gamma\rvert$	$\lvert\lambda_\gamma\rvert$	$\lvert\tilde{\kappa}_\gamma\rvert$
standard model	0.008 [33, 34]	0.002 [34]	10^{-22} [35, 36]
2HDM	0.016 [37]	0.0014 [37]	–
Multi-doublet	–	–	4×10^{-6} [38, 35]
E6	2.5×10^{-5} [39]	0.003 [39]	–
SUSY	0.005 [40]	5×10^{-5} [40]	3×10^{-4} [41]
TC	0.002 [42]	–	7×10^{-6} [42]
4th generation	–	–	5×10^{-3} [43]

  – See JE and J. Wudka, hep-ex/9804322

Diboson Production

- Effect of anomalous couplings:
  - Increased ***diboson production cross section***
  - Increased ***boson transverse momentum*** in diboson production
- Cross sections in the standard model at 1.96 TeV:

  $\sigma(W\gamma \to l\nu\gamma)$ = 16 pb*

  $\sigma(Z\gamma \to ll\gamma)$ = 3.9 pb*

  $\sigma(WW)$ = 13 pb

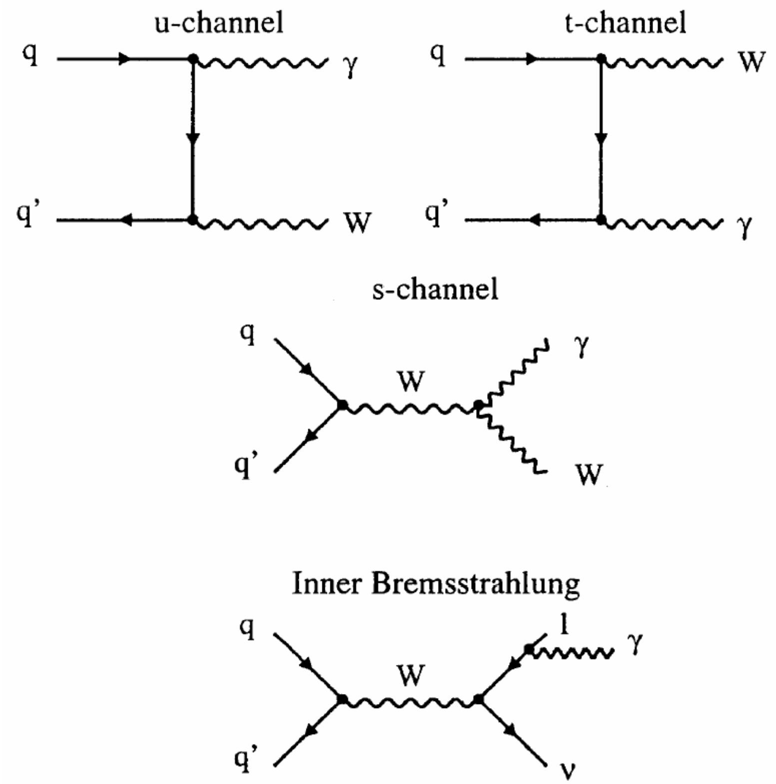
  $\sigma(WZ)$ = 3.7 pb

  * $E_T^\gamma > 8$ GeV, $\Delta R(l\gamma) > 0.7$

- Diboson production is an important background in many high-p_T analyses

  e.g. $H \to WW$, top, trileptons

- ***Wγ Production***
  - Probes $WW\gamma$ vertex
  - Main background is from W + jet production; jet mimics a photon
  - Radiative decays suppressed by requiring $E_T^\gamma > 8$ GeV, $\Delta R(l\gamma) > 0.7$

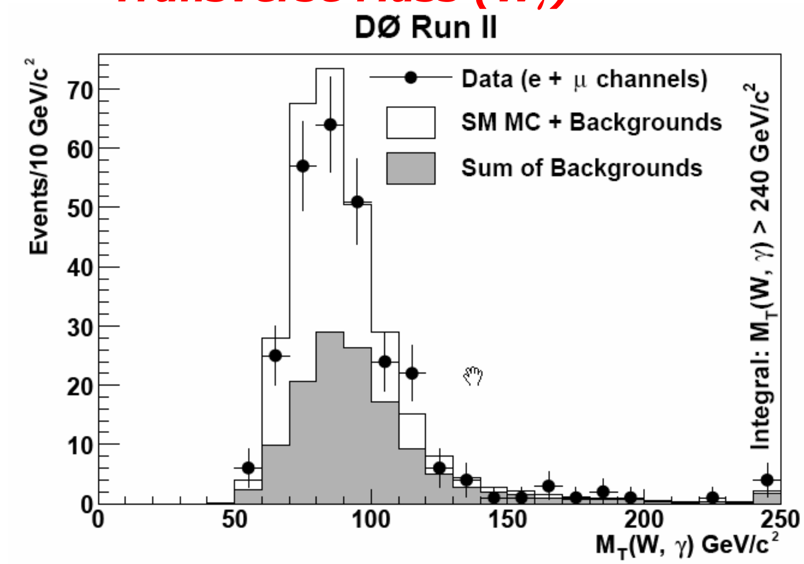


Wγ Production

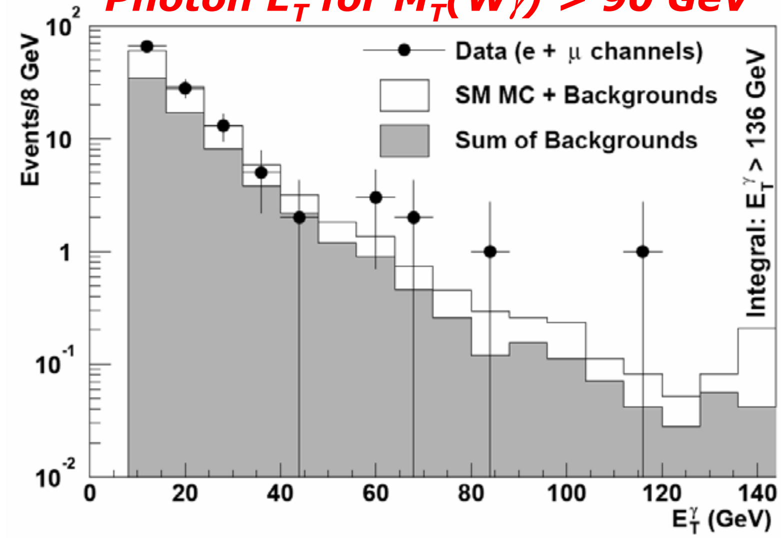
- Event selection $\int L dt = 162\ (e), 134 (\mu)\ \mathrm{pb}^{-1}$
  - High p_T electron or muon
  - Missing E_T > 25,20 GeV
  - Isolated photon with
    - E_T > 8 GeV, $|\eta|$ < 1.1
    - $\Delta R(l\gamma)$ > 0.7
- Background estimation
  - W + jet events from data
  - Probability for a jet to be misidentified as a photon
    - Estimated from multijet events in data
- SM predictions: Baur and Berger MC generator + parametrized detector simulation

Channel	*e*	*μ*
N_{obs}	112	161
N_{bkg}	60.8 ± 4.5	71.3 ± 5.2
$N_{obs} - N_{bkg}$	51.2 ± 11.5	89.7 ± 13.7

Transverse Mass (Wγ)



Photon E_T for $M_T(W\gamma)$ > 90 GeV



Results: Wγ Cross Section, WWγ Couplings

- Measured cross sections for Wγ production with E_T > 8 GeV and $\Delta R(l\gamma)$ > 0.7:

$\sigma(W\gamma \to e\nu\gamma)$ = 13.9 ± 2.9 (stat) ± 1.6 (syst) ± 0.9 (lum) pb

$\sigma(W\gamma \to \mu\nu\gamma)$ = 15.2 ± 2.0 (stat) ± 1.1 (syst) ± 1.0 (lum) pb

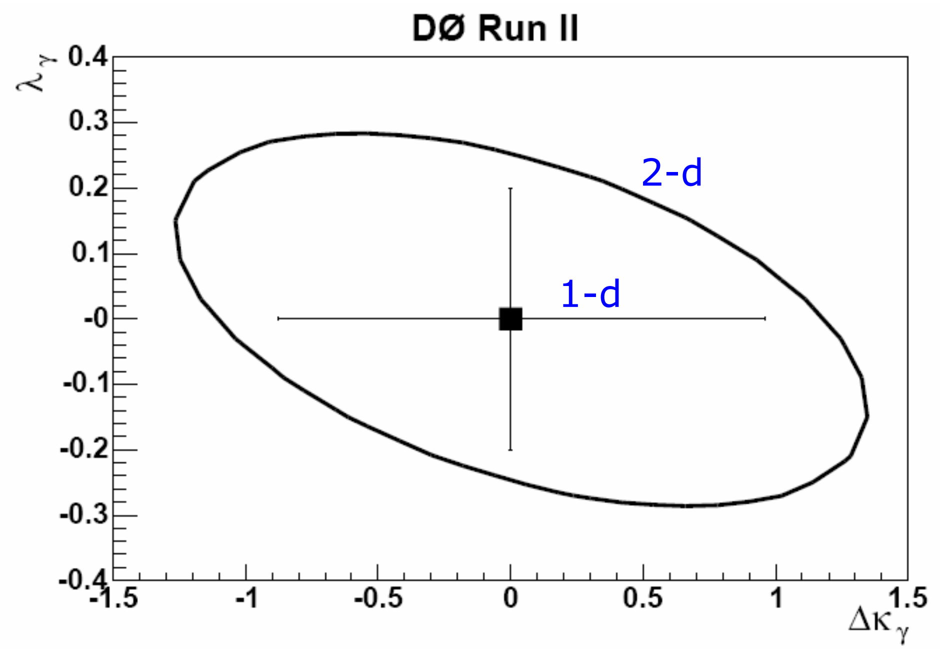
Combined Result:

$\sigma(W\gamma \to l\nu\gamma)$ = 14.8 ± 1.6 (stat) ± 1.0 (syst) ± 1.0 (lum) pb

Standard Model (Baur and Berger):

$\sigma(W\gamma \to l\nu\gamma)$ = 16.0 ± 0.4 pb

- Limits on couplings obtained from likelihood fit to photon E_T spectrum



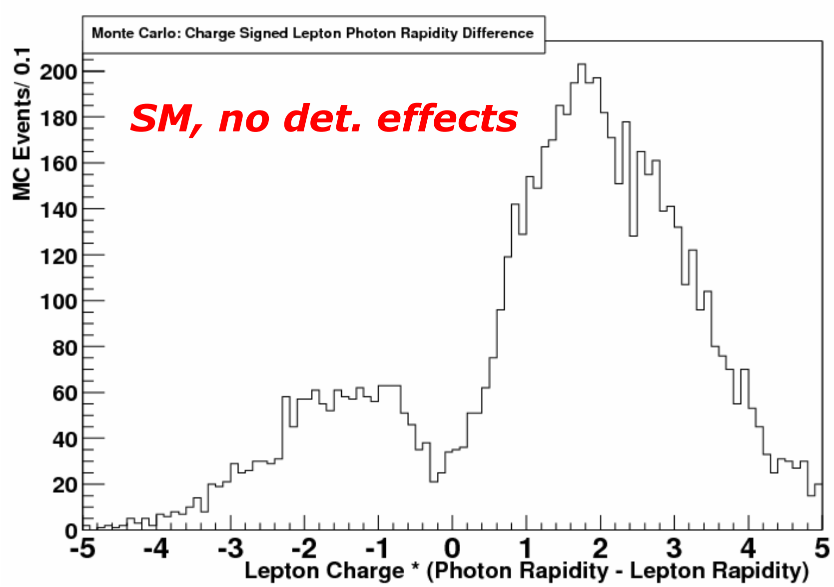
- 95% CL 1-d limits for Λ_{FF} = 2 TeV:

$$-0.88 < \Delta\kappa_\gamma < 0.96$$

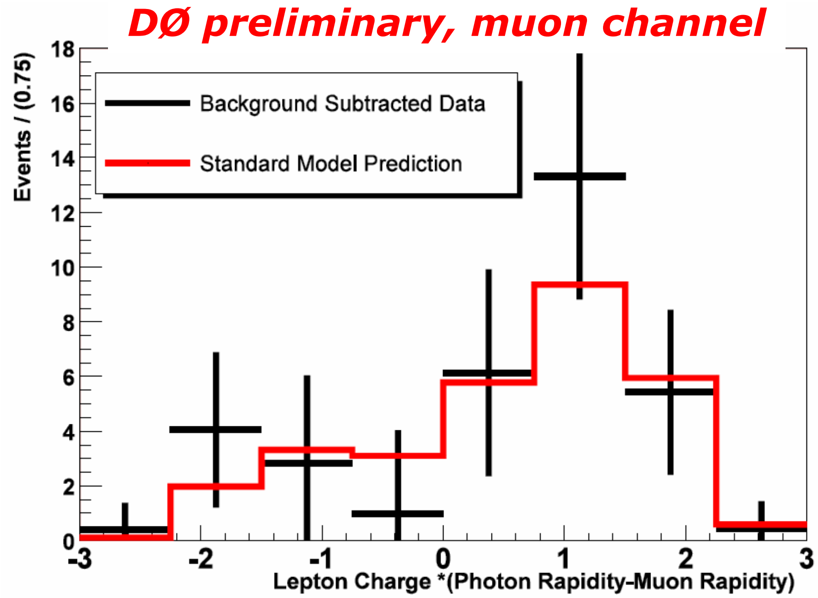
$$-0.20 < \lambda_\gamma < 0.20$$

Wγ Radiation Zero

- Radiation zero in all helicity amplitudes for Wγ production in SM
  - For $u\bar{d} \to W^+\gamma$, ***amplitudes vanish*** for cosθ = −1/3
  - θ = scattering angle of photon w.r.t. quark direction in Wγ rest frame
  - Corresponds to dip at η(γ) − η(l^+) ≈ −0.4



- In practice, zero is partially filled in
  - Effects of pdf's, higher-order QCD corrections, final state photon radiation



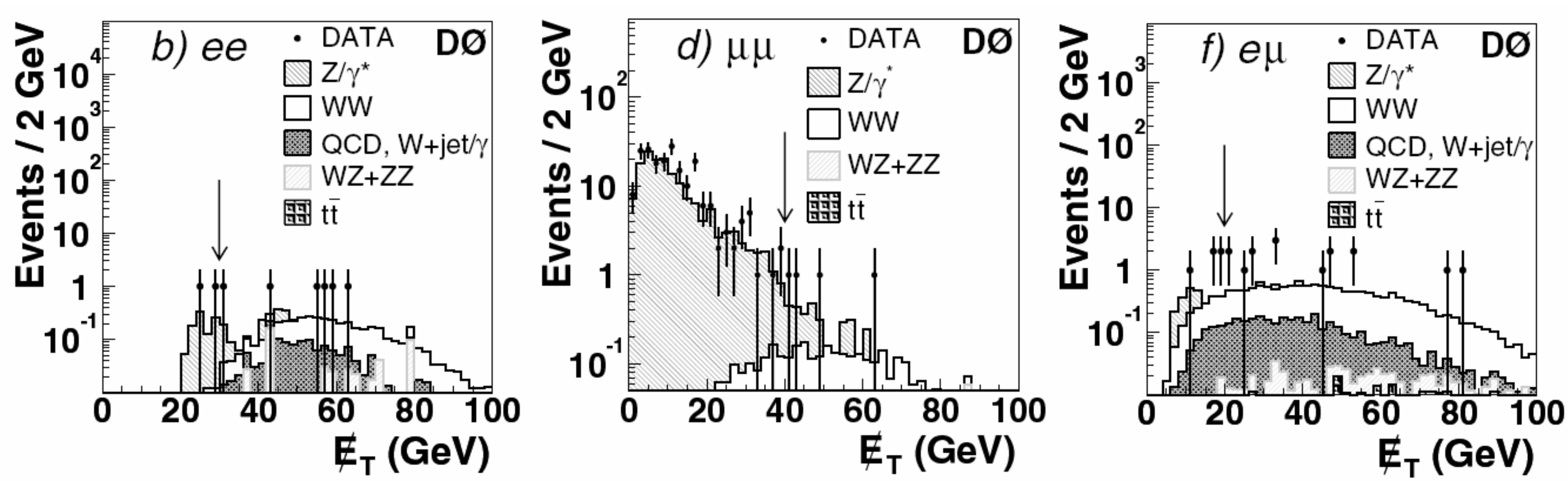
  - ***Wide η coverage essential***; extend for electrons and photons in future

WW Cross Section

- WW production

  $$p\bar{p} \rightarrow W^+W^- \rightarrow \ell^+\nu\ell'^-\nu'$$

  in three decay modes: ee, μμ, eμ
- Selection
  - $\int L dt = 252\,(ee), 224\,(\mu\mu), 235\,(e\mu)\ \mathrm{pb}^{-1}$
  - Two oppositely charged leptons with p_T > 15 GeV
  - At least one with p_T >20 GeV
- Additional selection based on
  - Missing E_T, m_T, Δφ(jet, $\not{E}_T$), Δφ(μ,μ), Σ E_T^{jet}, Z mass window
- Good agreement of data with SM WW production + backgrounds
- Monte Carlo
  - PYTHIA + parametrized detector simulation



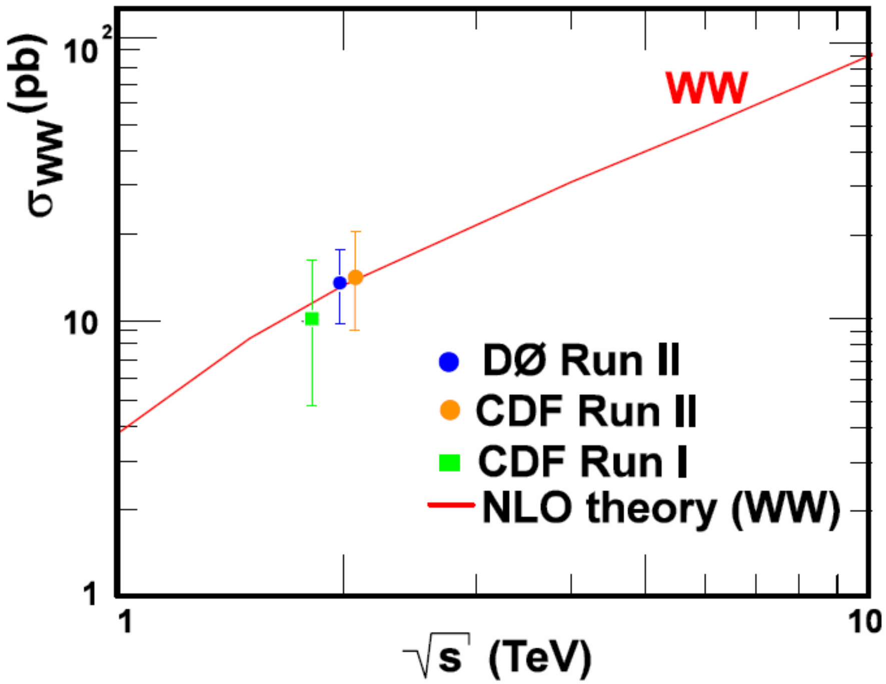
WW Cross Section Results

Channel	***ee***	***μμ***	***eμ***
N_{obs}	6	4	15
N_{bkg}	2.30 ± 0.21	1.95 ± 0.41	3.81 ± 0.17
$N_{WW(SM)}$	3.42 ± 0.05	2.10 ± 0.05	11.10 ± 0.10

- Probability of background fluctuation is very low: 5.2σ
- ***Measured cross section***

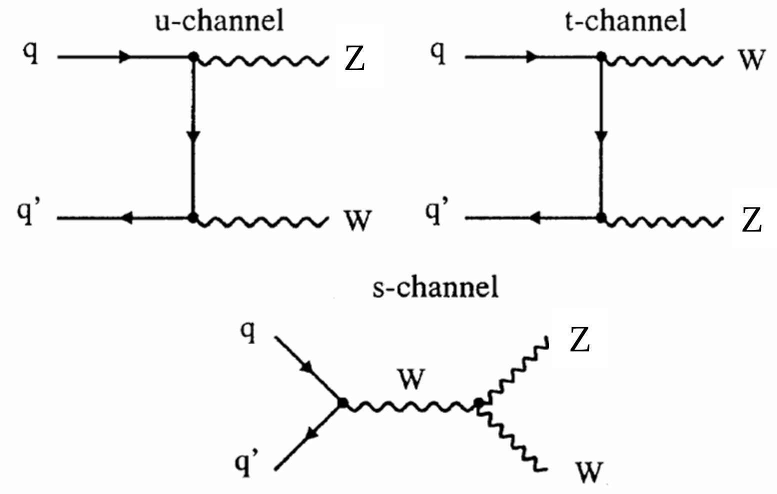
$$\sigma(p\bar{p} \to W^+W^-) =$$
$$13.8\,^{+4.3}_{-3.8}(\text{stat})\,^{+1.2}_{-0.9}(\text{syst}) \pm 0.9(\text{lum})\ \text{pb}$$

- Good agreement with NLO calculations 12.0-13.5 pb
  - Ohnemus/Campbell and Ellis



WZ Production

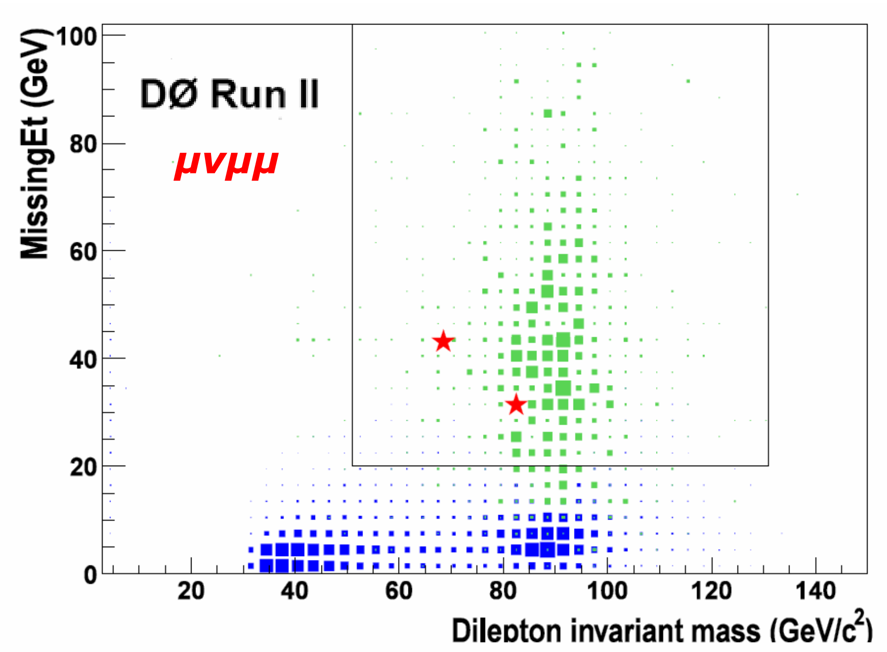
- Sensitive to WWZ vertex
  - cf. WW production, which depends on WWZ ***and*** WWγ
  - Allows study of WWZ coupling parameters with ***no assumptions*** about WWγ couplings
- SM cross section is 3.7 pb
- WZ $\rightarrow$ lν l^+l^- mode is clean and unambiguous
  - But has low branching fraction 1.5%
- WZ $\rightarrow$ lν jj mode has larger branching fraction (15%)
  - But cannot distinguish WZ from W+jets, WW

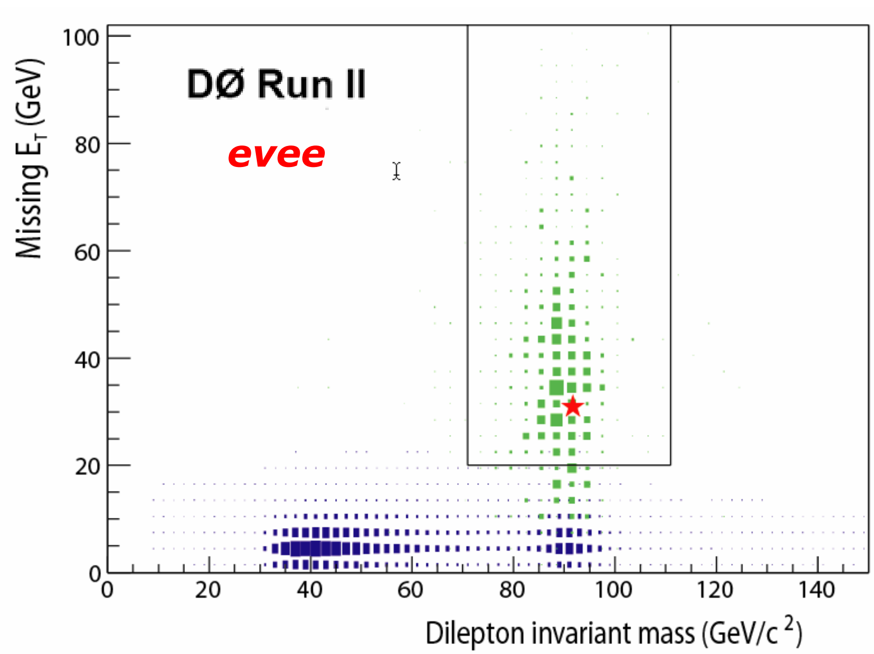


WZ → Trileptons

- Event selection
  - $\int L dt = 320\ (e\nu ee),\ 290\ (\mu\nu ee)$

    $280\ (e\nu\mu\mu),\ 290\ (\mu\nu\mu\mu)\ \mathrm{pb}^{-1}$
  - 3 charged leptons p_T > 15 GeV, missing E_T > 20 GeV, M_Z window
- Candidates:
  - 2 μν μμ events, 1 eν ee event
- Total estimated background = 0.71 ± 0.08
  - Z+jet background estimated from dilepton + jet events and P(j → e), P(j → μ)
  - Other backgrounds are from Zγ,ZZ, and ttbar





Results and Limits on WWZ Coupling

- Probability of background of 0.71 events to fluctuate to three or more candidates is 3.5%
  - Assume excess events due to WWZ signal: ***Cross section***

$$\sigma(p\bar{p} \to WZ) = 4.5\ ^{+3.8}_{-2.6}\ \text{pb}$$

$$< 13.3\ \text{pb at the 95\% C.L.}$$

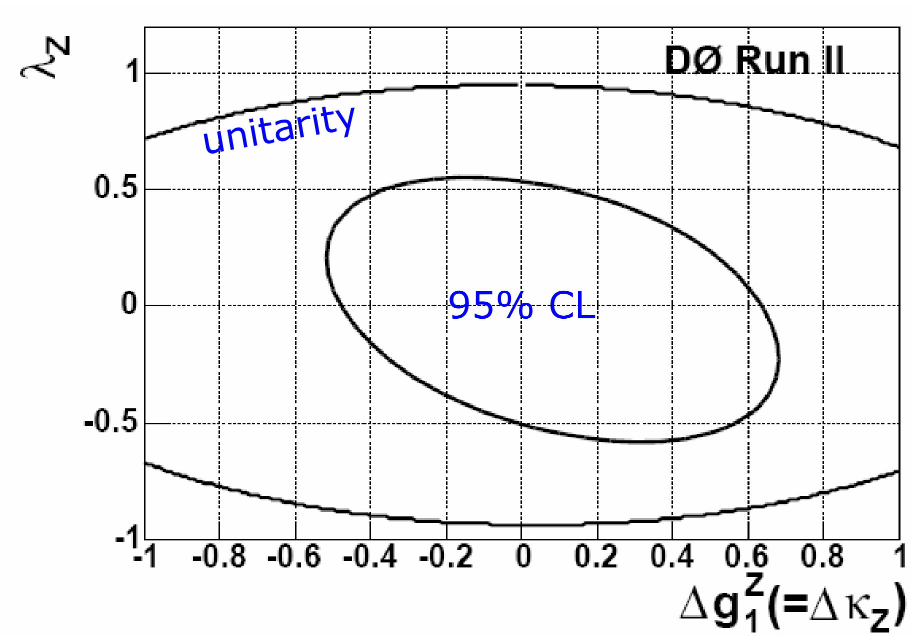
  - Agrees with SM (Campbell+Ellis)

$$\sigma_{SM}^{NLO}(p\bar{p} \to WZ) = 3.7 \pm 0.1\ \text{pb}$$

- 95% CL limits on WWZ coupling parameters for Λ_{FF}= 1.5 TeV:

Condition	***Limits***
$\Delta g_1^Z = \Delta\kappa_Z = 0$	$-0.53 < \lambda_Z < 0.56$
$\lambda_Z = \Delta\kappa_Z = 0$	$-0.57 < \Delta g_1^Z < 0.76$
$\lambda_Z = \Delta g_1^Z = 0$	$-2.0 < \Delta\kappa_Z < 2.4$
$\lambda_Z = 0, \Delta g_1^Z = \Delta\kappa_Z$	$-0.49 < \Delta g_1^Z = \Delta\kappa_Z < 0.66$

- 95%CL 2-d limits for for Λ_{FF}= 1.5 TeV, with $\Delta g_1^Z = \Delta\kappa_Z$:

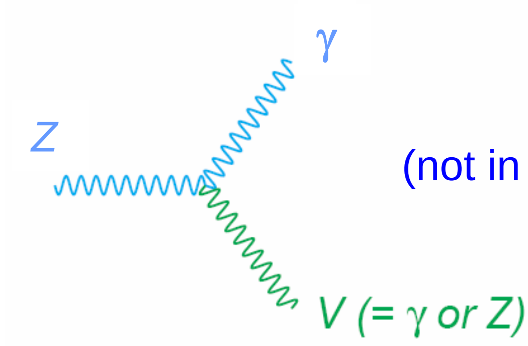


  - Limits are model-independent (no WWγ coupling assumptions)
  - Factor of ~3 better than Run I

Anomalous ZZγ and Zγγ Couplings

- ***Effective Lagrangian***

$$L_{Z\gamma V} = -ie\left[\left(h_1^V F^{\mu\nu} + h_3^V \tilde{F}^{\mu\nu}\right) Z_\mu \frac{\left(\Box + m_V^2\right)}{m_Z^2} V_\nu\right] - ie\left[\left(h_2^V F^{\mu\nu} + h_4^V \tilde{F}^{\mu\nu}\right) Z^\alpha \frac{\left(\Box + m_V^2\right)}{m_Z^4} \partial_\alpha \partial_\mu V_\nu\right]$$



- h_1^V and h_2^V violate CP; h_3^V and h_4^V conserve CP
- All coupling parameters are zero in the SM at tree-level
- Form factor to ensure unitarity

$$a(\hat{s}) = \frac{a_0}{\left(1 + \hat{s}/\Lambda_{FF}^2\right)^n} \quad \begin{cases} \hat{s} = \text{subprocess CM energy} \\ \Lambda_{FF} = \text{form factor scale} \end{cases}$$

$$n = 3 \text{ for } h_{1,3}^V \text{ and } n = 4 \text{ for } h_{2,4}^V$$

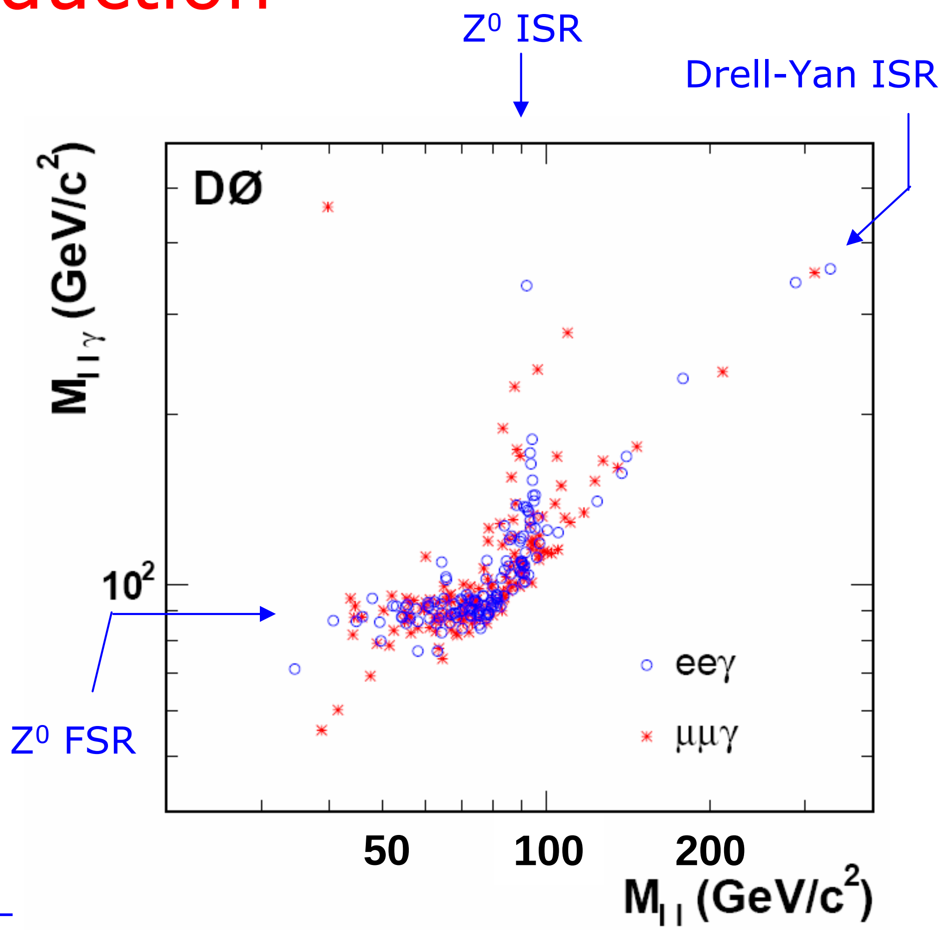
- ZZγ couplings related to ***transition moments of the Z***, e.g.

$$\mu_W = \frac{-e}{\sqrt{2}m_Z}\frac{E_\gamma^2}{m_Z^2}\left(h_1^Z - h_2^Z\right)$$

$$Q_Z^e = \frac{2\sqrt{10}e}{m_Z^2} h_1^Z$$

Zγ Production

- Two charged leptons
  - p_T >15/25 GeV (ee)
  - p_T > 15/15 GeV (μμ)
- M(ll) > 30 GeV
- Photon requirements same as in Wγ analysis
  - E_T > 8 GeV
  - ΔR(lγ) > 0.7
  - |η| < 1.1
- Data sets:
  - 286 pb^{-1} (μμ), 324 pb^{-1} (ee)
- Main background is from Z + jet, where jet mimics a photon



Channel	ee	μμ
N_{obs}	138	152
N_{bkg}	23.6 ± 2.3	22.4 ± 3.0
$N_{Z\gamma(SM)}$	95.3 ± 4.9	126.0 ± 7.8

- Sample is a factor of 10 larger than in Run I

Zγ Results

- Measured cross section for Zγ production with $E_T^\gamma > 8$ GeV, $\Delta R(l\gamma) > 0.7$, and $M(ll) > 30$ GeV:

$$\sigma(Z\gamma \to ll\gamma) = 4.2 \pm 0.4(\text{stat+syst}) \pm 0.3(\text{lum})\ \text{pb}$$

  - Good agrement with SM (Baur, Han, and Ohnemus):

$$\sigma_{SM}^{NLO}(Z\gamma \to ll\gamma) = 3.9^{+0.1}_{-0.2}\ \text{pb}$$

- Limits on anomalous couplings set using maximum likelihood fit to photon E_T spectrum
- 95% CL 1-d limits for $\Lambda_{FF} = 1$ TeV:

$$-0.23 < h_{10,30}^{Z} < 0.23$$

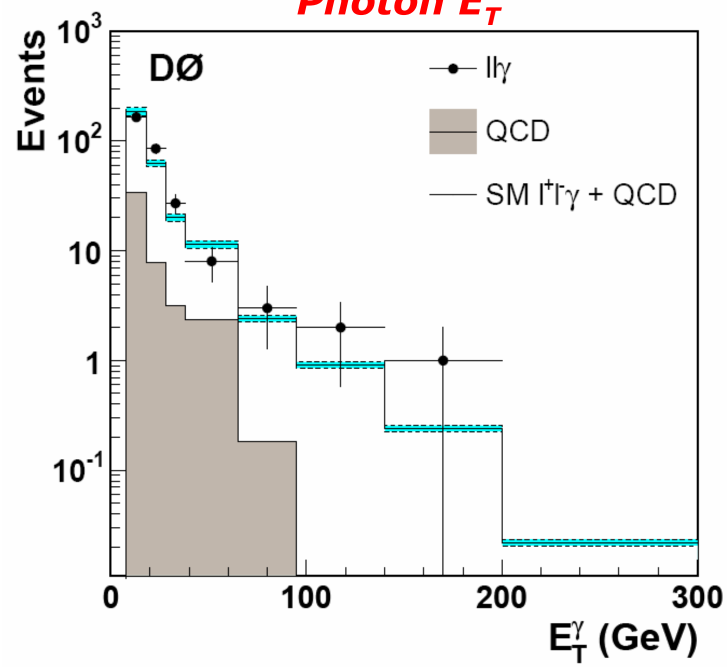
$$-0.020 < h_{20,40}^{Z} < 0.020 \longleftarrow$$

$$-0.23 < h_{10,30}^{\gamma} < 0.23$$

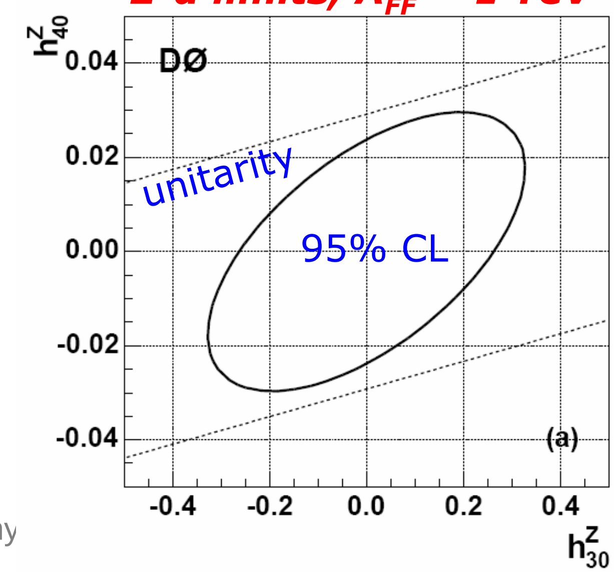
$$-0.019 < h_{20,40}^{\gamma} < 0.019 \longleftarrow$$

Best limits to date

Photon E_T



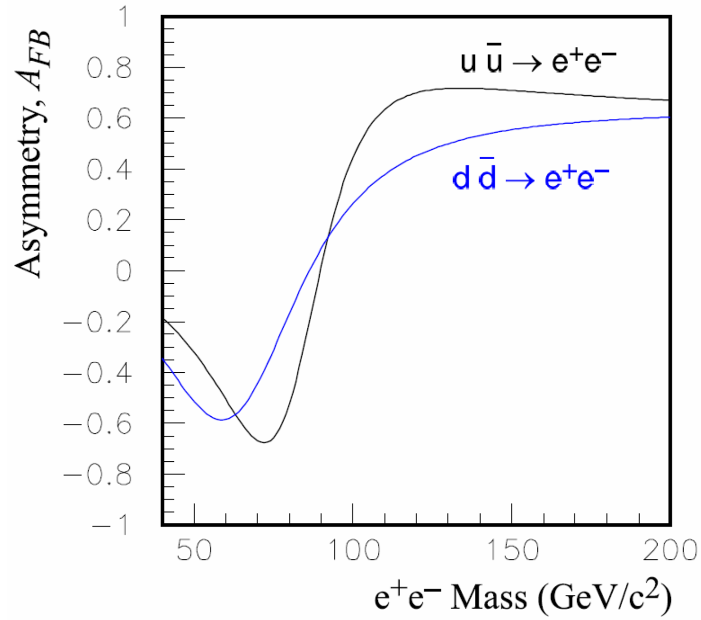
2-d limits, Λ_{FF} = 1 TeV

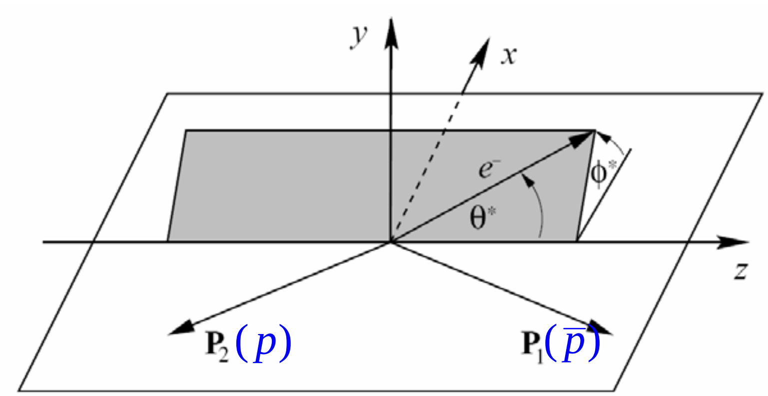


Drell-Yan Production and A_{FB}

- Forward-backward asymmetry depends on v and a-v couplings of the quarks and leptons to the Z
  - Sensitive to $\sin^2\theta_W$, but need high luminosity (see JE, J. Rha, and U. Baur, hep-ex/0011009)
- Can measure A_{FB} at cm energies above LEP II energy
  - Confirm γ^*/Z interference (dominates at high cm energy)
  - Study possible new phenomena that affects A_{FB} , e.g. Z', extra dimensions,…
  - $A_{FB} \sim 0.6$ in SM
- Electron angle measured in Collins-Soper frame
- Select ee events
  - Electron $E_T > 25$ GeV, $|\eta| < 1.1$
  - At least one EM cluster must have a track match (with E/p)
    - Charge sign measurement
  - Int. lum. $= 177\ pb^{-1}$

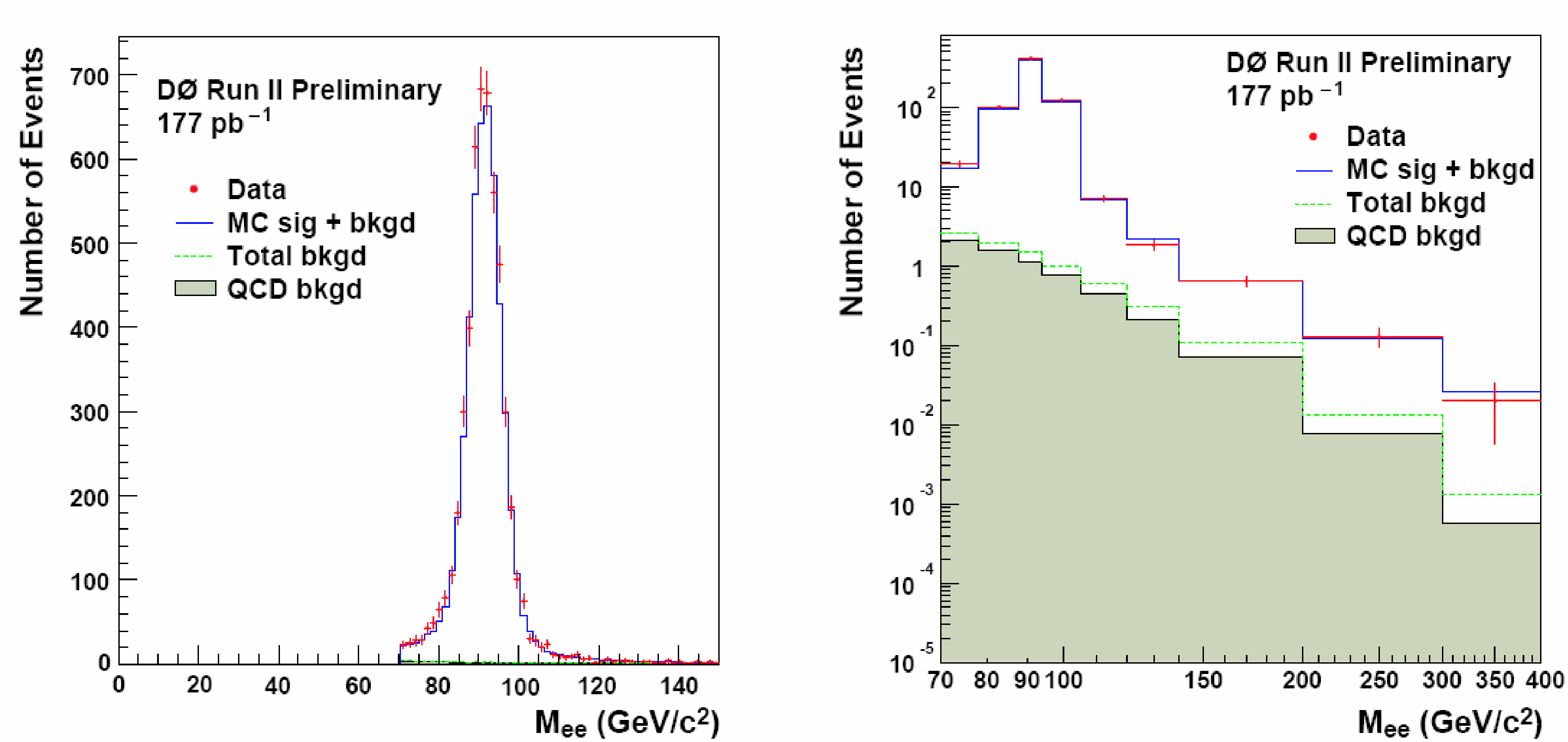
$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$





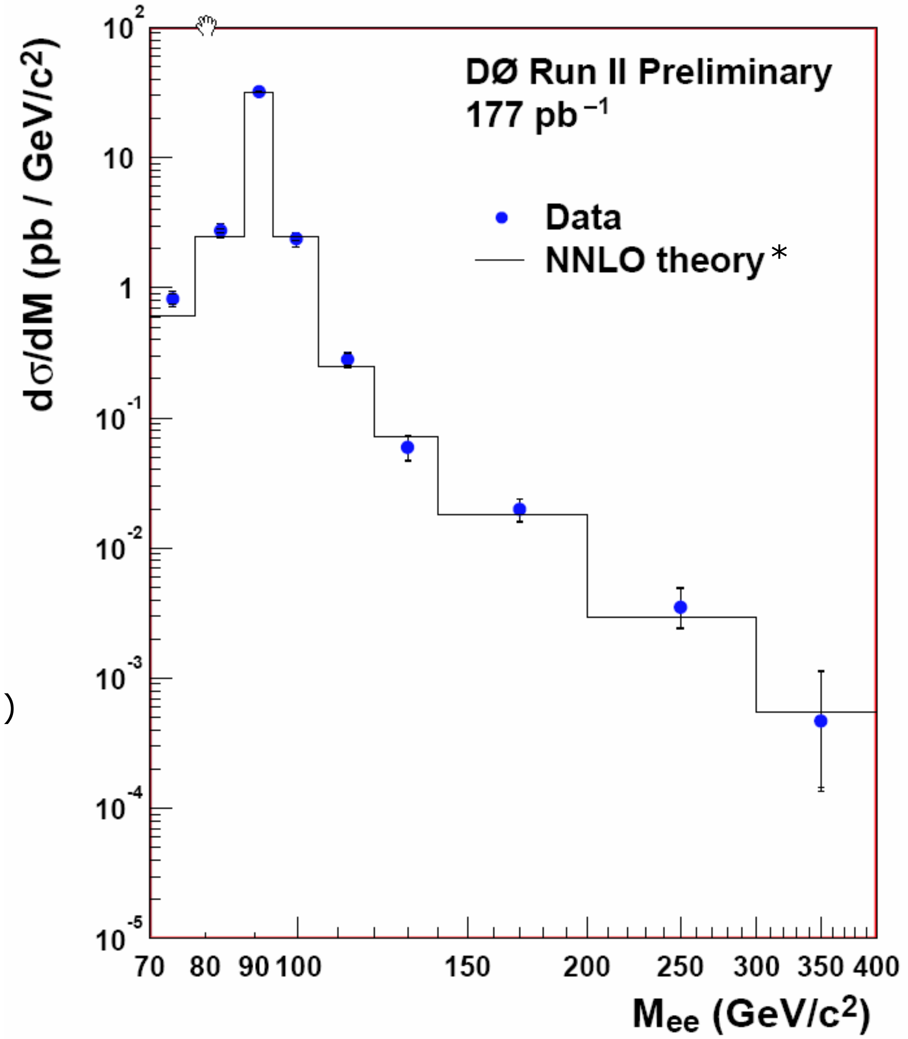
M_{ee}: Data – Monte Carlo Comparison

- 5259 candidates for M_{ee} > 70 GeV
- Monte Carlo
  - PYTHIA/PHOTOS event generator
  - M_{ee}-dependent K-factor to account for $O(\alpha_s^2)$ QCD corrections
  - Parametrized detector simulation
- Main background is from multijet events; jets mimic electrons
  - N_{QCD} = 62.5 ± 8.0
- Other backgrounds much smaller
  - Main one is W+jets (11.1 ± 3.4)



Drell-Yan Differential Cross Section

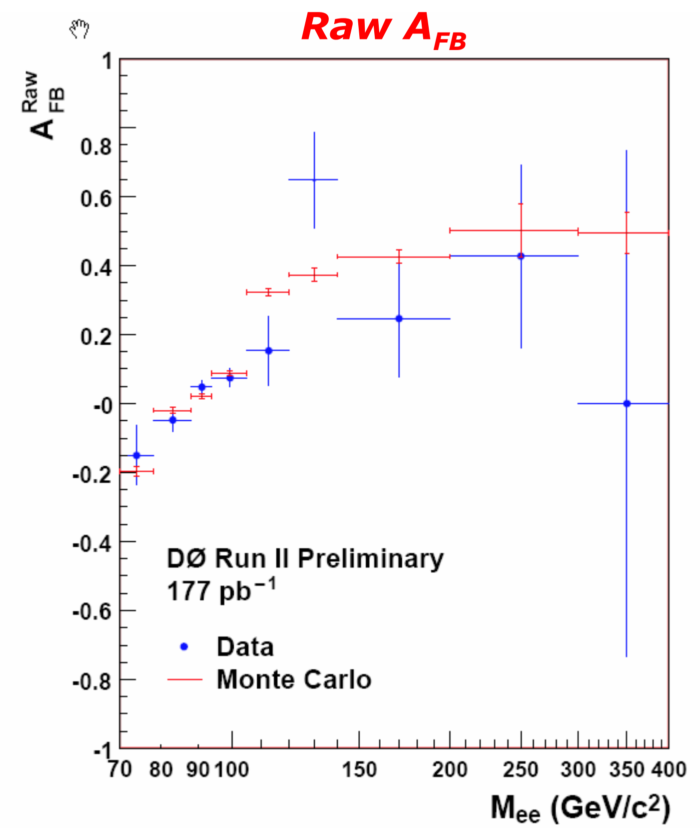
- Differential Drell-Yan cross section obtained by correcting for
  - Kinematic acceptance
  - Geometric acceptance
  - Detector resolution
  - QED final state radiation
  - Detection efficiencies
  - Backgrounds
- Observe agreement with NNLO QCD calculations

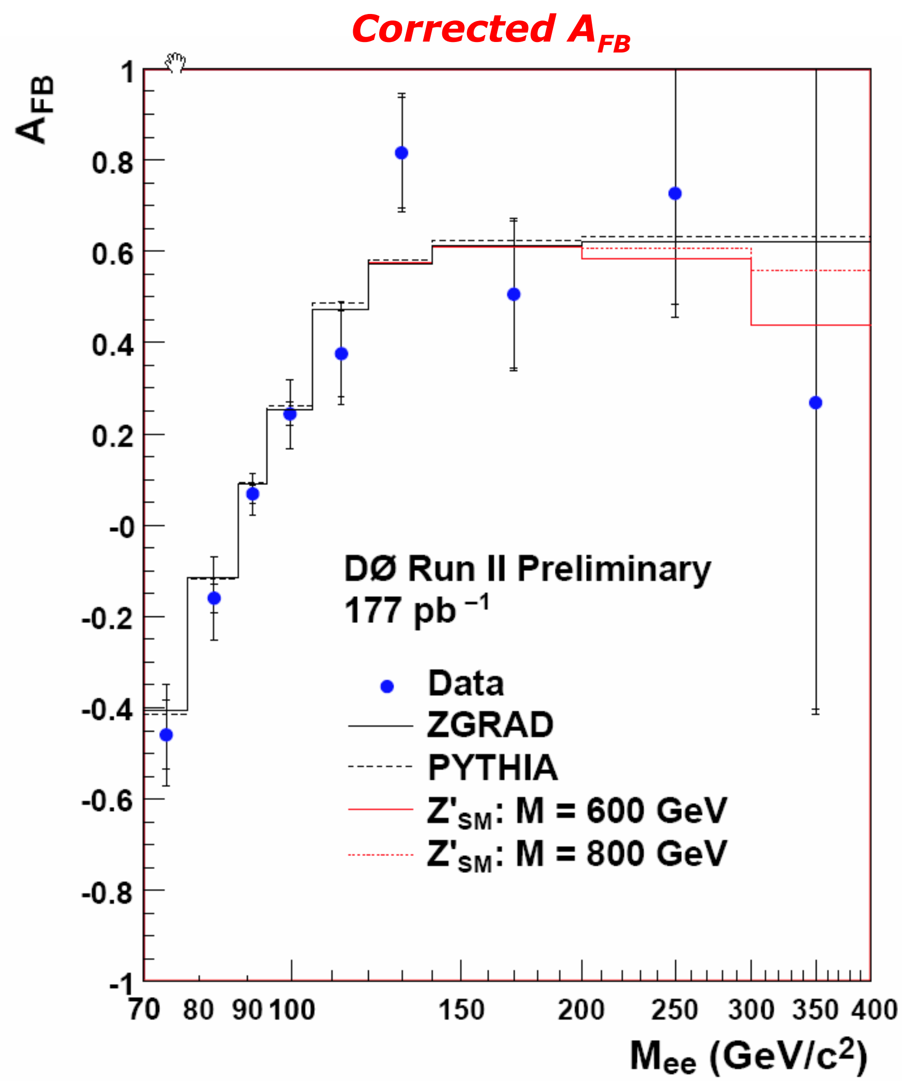


* $O(\alpha_s^2)$ calculation:
Hamberg, van Neerven and Matsuura, Nucl. Phys. B 359, 343 (1991);
van Neerven and Zijlstara, Nucl. Phys. B 382, 11 (1992)

A_{FB} Results

- Data agree with SM Monte Carlo prediction
  - Consistent with $A_{FB} \sim 0.6$ at high M_{ee}





Summary

- Studies of $W\gamma$ production
  - Model-independent limits on $WW\gamma$ couplings
  - Looking for radiation zero
- $WW \rightarrow$ dileptons production cross section is consistent with NLO SM calculation
  - Understanding is important for Higgs search
- Evidence for WZ production (trileptons)
  - Model-independent limits on WWZ couplings
- Studies of $Z\gamma$ production
  - Factor of 10 more statistics than Run I
  - Limits on h_{20}, h_{40} are the best to date
- Drell-Yan
  - Differential cross section $d\sigma/dM_{ee}$ and forward-backward asymmetry; consistent with SM predictions